

The impact of metallicity and dynamics on the evolution of young star clusters

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Abstract The early evolution of a dense young star cluster (YSC) depends on the intricate connection between stellar evolution and dynamical processes. Thus, N-body simulations of YSCs must account for both aspects. We discuss N-body simulations of YSCs with three different metallicities ($Z = 0.01, 0.1$ and $1 Z_{\odot}$), including metallicity-dependent stellar evolution recipes and metallicity-dependent prescriptions for stellar winds and remnant formation. We show that mass-loss by stellar winds influences the reversal of core collapse. In particular, the post-collapse expansion of the core is faster in metal-rich YSCs than in metal-poor YSCs, because the former lose more mass (through stellar winds) than the latter. As a consequence, the half-mass radius expands more in metal-poor YSCs. We also discuss how these findings depend on the total mass and on the virial radius of the YSC. These results give us a clue to understand the early evolution of YSCs with different metallicity.

1 Introduction

The densest young star clusters (YSCs) are collisional environments: their central two-body relaxation timescale (t_{rlx}) is generally shorter than 100 Myr. For a realistic initial mass function (IMF), YSCs are expected to undergo core collapse (CC) in less than t_{rlx} . The reversal of CC is generally ascribed to hard binaries (i.e. binaries whose binding energy is higher than the average kinetic energy of a star in the cluster), because they transfer kinetic energy to stars through three-body encounters.

It has long been debated whether mass-loss by stellar winds and/or supernovae (SNe) is efficient in affecting CC (e.g. Mapelli & Bressan 2013, and references therein). Stellar winds and SNe eject mass from a star cluster, making the central potential well shallower and quenching the onset of gravothermal instability. Furthermore, stellar winds are expected to depend on metallicity (Z): metal-poor stars lose less mass than metal-rich ones (e.g. Vink et al. 2001). Thus, the effect of stellar winds on CC is expected to be stronger at high Z . In this paper, we investigate the impact of Z -dependent stellar winds and SNe on the CC of YSCs, by means of direct-summation N-body simulations.

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2 Method and simulations

We adopt the STARLAB public software environment (Portegies Zwart et al. 2001), in the version modified by Mapelli et al. (2013). This version includes recipes for Z -dependent stellar evolution (Hurley et al. 2000), stellar winds (Vink et al. 2001) and direct collapse of massive metal-poor stars (Mapelli et al. 2009). The initial conditions of the simulated YSCs have been generated following a King profile. The mass of each simulated particle (which corresponds to a single star) has been randomly drawn from a Kroupa IMF with minimum and maximum mass 0.1 and 150 M_{\odot} , respectively. The runs discussed in this paper are the following.

Set A: 300 N-body realizations of YSCs with virial radius $r_{\text{vir}} = 1$ pc, dimensionless central potential $W_0 = 5$, particle number $N_* = 5 \times 10^3$. These runs have already been discussed in Mapelli & Bressan (2013).

Set B: 30 N-body realizations of YSCs with $r_{\text{vir}} = 1$ pc, $W_0 = 5$, $N_* = 5 \times 10^4$.

Set C: 30 N-body realizations of YSCs with $r_{\text{vir}} = 5$ pc, $W_0 = 5$, $N_* = 5 \times 10^4$.

In each set of simulations, 1/3 of the runs have $Z = Z_{\odot}$, 1/3 have $Z = 0.1 Z_{\odot}$ and 1/3 have $Z = 0.01 Z_{\odot}$. The structural parameters (core radius r_c , half-mass radius r_{hm} , half-light radius r_{hl} and total binary binding energy E_b) discussed in the following are the median value of different N-body realizations (with the same Z) in each set of runs, to filter out statistical fluctuations.

3 Results

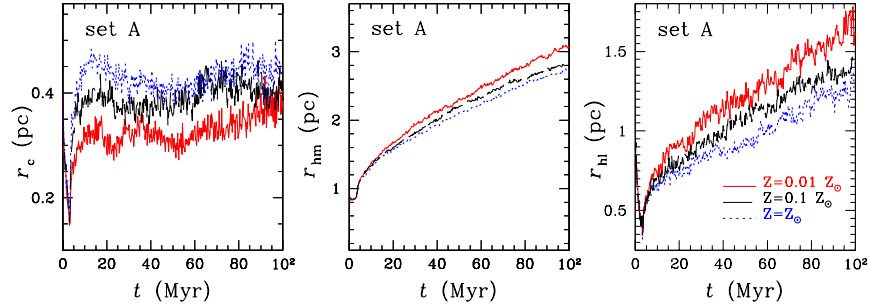


Fig. 1 Core radius r_c (left-hand panel), half-mass radius r_{hm} (central panel) and half-light radius r_{hl} (right-hand panel) as a function of time for $Z = 0.01 Z_{\odot}$ (red solid line), $0.1 Z_{\odot}$ (black dashed line) and $1 Z_{\odot}$ (blue dotted line). Runs of set A are shown ($W_0 = 5$, $r_{\text{vir}} = 1$ pc, $N_* = 5 \times 10^3$). Each line is the median value of 100 N-body realizations.

Fig. 1 shows the behaviour of r_c , r_{hm} and r_{hl} in the runs of set A, for different Z . The YSCs in set A undergo CC at $t \sim 2 - 3$ Myr (regardless of Z). The impact of Z -dependent stellar winds and SNe is apparent in the reversal of CC: r_c increases faster

in metal-rich YSCs, because stellar winds are stronger than in metal-poor YSCs. At the same time, r_{hm} expands more in metal-poor YSCs than in metal-rich YSCs. The reason is that three-body encounters are more efficient in metal-poor YSCs (where higher core densities are reached during the CC) and inject more kinetic energy in the halo. The same trend is apparent in the half-light radius r_{hl} : it expands more in metal-poor YSCs than in metal-rich ones. Furthermore, the difference between the half-light radii of metal-rich and metal-poor YSCs is a factor of two larger than the difference between the half-mass radii, due to mass segregation and to the Z -dependence of the stellar luminosity (Mapelli & Bressan 2013).

How much do these results depend on the mass and on the size of YSCs? The left-hand column of Fig. 2 shows the behaviour of r_{c} and r_{hm} in runs of set B, which are 10 times more massive than runs of set A, even if they have the same size ($r_{\text{vir}} = 1$ pc). The CC occurs again at $t \sim 2 - 3$ Myr. r_{c} and r_{hm} show the same trend in set B and in set A. The right-hand column of Fig. 2 shows the behaviour of r_{c} and r_{hm} in runs of set C, which are as massive as runs of set B but have larger size ($r_{\text{vir}} = 5$ pc). Thus, the YSCs of set C have lower central density, and the CC is expected to occur at later times ($t_{\text{rlx}} \propto r_{\text{hm}}^{3/2}$). In fact, the CC begins at ~ 60 Myr for $Z = 0.01 Z_{\odot}$ and at later times for higher Z . In the metal-rich ($Z = 0.1, 1 Z_{\odot}$) YSCs of set C the CC is delayed, because the mass-loss by stellar winds is sufficient to keep the core stable against collapse. This implies that r_{hm} is marginally larger in metal-rich YSCs than in metal-poor ones, until the CC begins. During the CC, the half-mass radius of metal-poor YSCs starts expanding faster than that of metal-rich YSCs, producing the same trend as observed in set A and B.

This interpretation is confirmed by the top row of Fig. 2, which shows the total binding energy of binaries E_{b} (considering all binaries in a YSC at a given time). Since we do not include primordial binaries in our simulations, E_{b} represents the total energy that is stored in binaries as a consequence of three-body encounters. The YSCs of set C have $E_{\text{b}} \sim 0$ up to $t \sim 60$ Myr. In contrast, E_{b} in runs of set B grows dramatically during the first CC, decreases during the rapid expansion phase and grows steadily at later times. Thus, three-body encounters are almost negligible in the loose YSCs of set C, while they are the main engine of CC reversal in sets A and B.

4 Conclusions

We have shown that stellar winds are very important in the early evolution of YSCs and that their effects strongly depend on Z . In particular, the post-collapse re-expansion of the core is faster for metal-rich YSCs than for metal-poor YSCs, because the former lose more mass (through stellar winds) than the latter. As a consequence, the half-mass radius and the half-light radius expand faster in metal-poor YSCs. The initial size of the YSC plays a critical role, because the relaxation timescale and thus the onset of CC strongly depend on it ($t_{\text{rlx}} \propto r_{\text{hm}}^{3/2}$). The total mass of the YSC has only marginal effects. Other YSC properties (e.g. W_0) deserve further

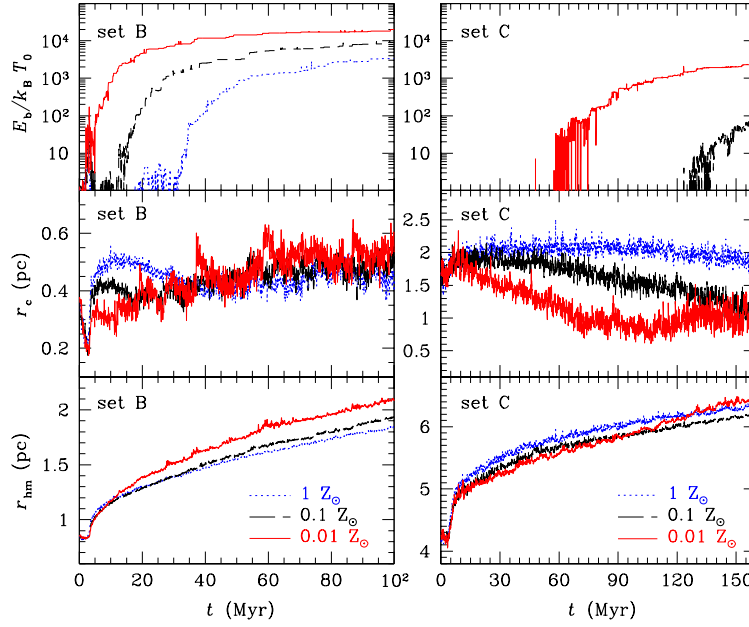


Fig. 2 Total binary binding energy E_b (top panel), core radius r_c (central panel) and half-mass radius r_{hm} (bottom panel) as a function of time for $Z = 0.01 Z_\odot$ (red solid line), $0.1 Z_\odot$ (black dashed line) and $1 Z_\odot$ (blue dotted line). E_b is normalized to the average initial kinetic energy of a star in the YSC ($k_B T_0$). Each line is the median value of 10 runs. Left-hand panel: set B ($W_0 = 5$, $r_{vir} = 1$ pc, $N_* = 5 \times 10^4$). Right-hand panel: set C ($W_0 = 5$, $r_{vir} = 5$ pc, $N_* = 5 \times 10^4$).

investigation. Furthermore, the Z -dependence of stellar winds is still barely understood, especially in the post-main sequence evolution. Thus, forthcoming studies will also investigate the effects of different recipes of mass-loss by stellar winds.

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